Study of mechanisms of sub-mm wave emission from plasma due to two-stream instability of relativistic electron beam

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Abstract - The original project of a sub-mm wave generator (frequency interval 0.1÷1 THz) based on transformation of plasma waves pumped by a high-current relativistic electron beam is developed at the GOL-PET facility. Results of recent experimental studies, theoretical analysis and computer simulations for this scheme of sub-mm wave generation are presented in the paper.

Introduction. Study of mechanisms of electromagnetic wave emission from magnetized plasma due to development of the two-stream instability of a high current relativistic electron beam (REB) is considerably important. The two-stream instability is a fundamental process occurring in both space and laboratory plasmas. In laboratory experiments, the beam-plasma interaction allows one to generate high-power sub-mm waves with the promptly varying frequency that is important for practical applications. In this paper, we present novel results on the study of mechanisms of sub-mm wave emission produced in a REB-plasma system because of the development of the two-stream instability.

Facility and results of experiments. For study of the conditions related with generation of electromagnetic radiation, a specialized facility GOL-PET was constructed (see. Fig. 1). The facility consists of an open magnetic trap with a multiple-mirror or uniform magnetic field of mean value B = 4.2 T and length L = 2.4 m between the end mirrors. The end mirrors have a strong field up to B = 8 T. A plasma column with the density $n_e \approx (0.2÷5)\times10^{15}$ cm^{-3} and a diameter of 7 cm is created by a longitudinal high-current discharge. U-2 accelerator producing a high current relativistic electron beam (REB) is mounted at one end of the trap. It produces the beam with the current I ~ 20kA, the pulse duration τ ≈ 6 μs at the electron kinetic energy E_e ≈ 0.8 MeV. The REB is injected into the end of the plasma column and where the beam diameter is 4 cm at the magnetic field 4 T. The radial profile of the plasma density is measured in 9-dots over the column diameter at a distance z = 0.83 m from the entrance mirror by diagnostics based on Thomson scattering. Dynamics of the average plasma density is measured by Michelson interferometer at z = 1.16 m. Pulsed current transformers measure the electron beam current at different axial points. Electron energy of REB is determined according with accelerator voltage

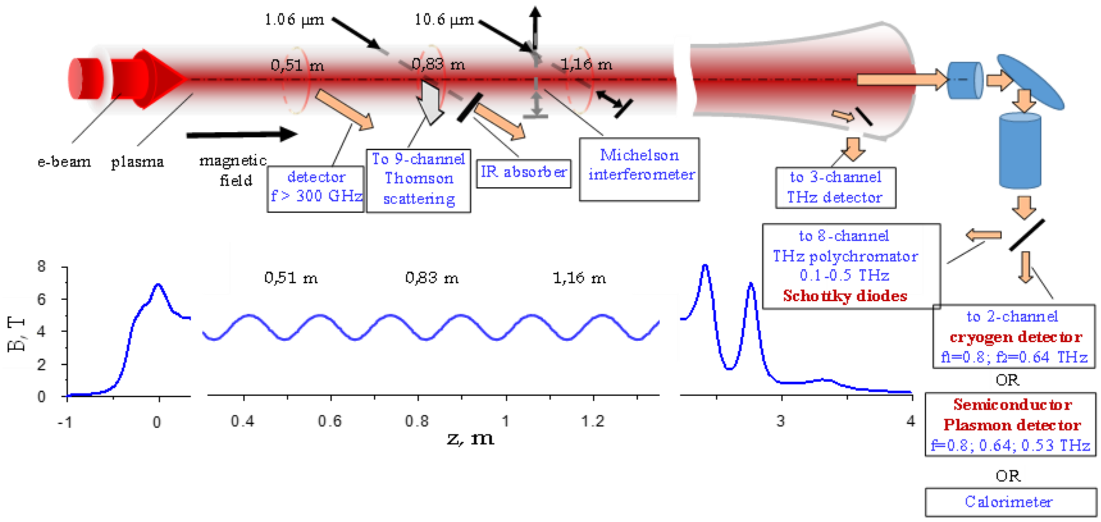
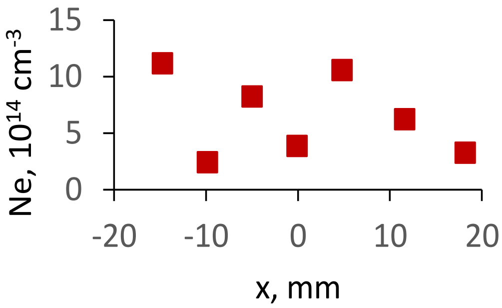


Fig.1. Schematic of experiment at the GOL-PET facility.

in the U-2 diode. The transfer of energy from REB to plasma is calculated from results of measurements of diamagnetism of the plasma column. The 8-channel sub-mm polychromator [8], as well as a number of single detectors with bandpass filters at their entrance are utilized to study properties of radiation emitted by plasma.

Previous experiments showed that the variation of the power value of the emitted electromagnetic waves correlated with the changes in the efficiency of plasma heating by the electron beam. [1-3]. A series of experiments on the simultaneous registration of radiation power emitted along the axis and in the perpendicular direction was carried at different plasma densities from 10^{14} up to 10^{15} cm^{-3}. The radiation emitted across the confining magnetic field (in the central part of the plasma column) was observed only at relatively low plasma densities $n_e < 5\times10^{14}$ cm^{3}. For higher value of plasma density, the emission in the band above 300 GHz was observed only along the axis of the device. Just as in the earlier experiments on the GOL-3, the EM-wave emission mainly exists simultaneously with the increasing of the plasma diamagnetism.

For the plasma density higher than 5×10^{14} cm^{-3}, we carried out a series experiments for measuring the temporal dynamics of radiation spectra emitted along the axis. It was done by the 8-channel polychromator with semiconductor diodes for the frequency interval from 0.1 up to 0.5 THz and by single plasmonic detectors and an additional 2-channel system of cryogenic sensors for the interval 0.5÷0.9 THz (see Fig. 1). Experiments showed that at plasma density $(0.5\div1)\times10^{15}$ cm^{-3} the spectral composition of the emission along the axis of the plasma column depended on radial gradient of the plasma density [2, 3]. The increase of the gradient caused to strongly increasing the spectral power density in the frequency band 150÷300 GHz. An example of signals from various sensors for one of the pulses of the GOL-PET facility (#1945) in case of the strong plasma density gradient (greater than 10^{15} cm^{-4}) is presented in Fig. 2. The signal of the spectral power density from the diodes in the interval 150÷300 GHz is dumped in 50 times for presenting here. Taking into account, this dumping factor one can say that the spectral



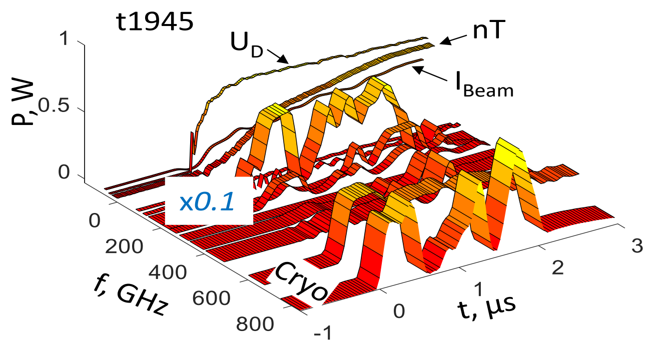


Fig.2. Results of measurements in pulse #1945 at the GOL-PET facility. Left part (a) is the plasma density distribution that was measured by the Tomson scattering system; right part (b) presents the signals from various sensors. U_D – diode voltage of the accelerator (MeV), I_{Beam} – beam current (10 kA), nT – plasma pressure measured by a diamagnetic loop, other signals are radiation power in frequency selective detectors (W).

power density in the interval 150÷300 GHz is greater than its value in the interval 400÷800 GHz approximately in two orders of the value. Basing on such results of measurements of the radiation emitted along the plasma column axis, we obtained the spectral power density distribution in the band from 0.1 up to 1 THz. The spectrum of the radiation is shown in Fig. 3. One can see in Fig. 3 that the spectrum contains two local peaks: the first is small one at the frequency less than 100 GHz, the second is very high in the range from 125 to 250 GHz. Then, there is a very wide frequency interval from 400 up to 800 GHz with spectral power density in 50 times less than in an area of around 200 GHz.

Short analysis of the results of measurements. The small peak of the spectral power density at the frequency near 100 GHz is ten times lower than the peak of the radiation in the 125÷250 GHz band. Since the frequency of the radiation in the 100 GHz range does not change when we vary the plasma density, we can assume that this radiation is produced by the cyclotron movement of beam electrons. The signals in the frequency band 125÷250 GHz are interpreted as radiation near the plasma frequency. Such radiation can be produced trough the linear mode conversion of upper-hybrid branch of plasma oscillations on plasma density gradients [4]. If we assume that EM radiation is really generated at the local plasma frequency inside the region with high transverse density gradients shown in Fig. 2a, the frequency spectrum of this radiation should be wider than the observed one in Fig.3a. The observed width of the spectral line corresponds to the limited range of plasma density $(3\div6)\times10^{14}$ cm^{-3}. It means that intense beam-driven oscillations are localized near the bottom of density wells visible in Fig. 2a. Even if these oscillations convert their energy to electromagnetic plasma modes, this radiation has no chance to escape from the plasma in the transverse direction. The typical transverse size of density wells with localized plasma oscillations equals to 4÷5 mm which corresponds to 2÷3 wavelengths of resonant beam-driven waves. Such a narrow region of intense beam-plasma interaction favors the growth of longitudinally propagating waves which cannot be converted to EM waves on purely transverse density gradients. However, if the plasma density in such a narrow well is modulated in the longitudinal direction due to, for example, the modulation

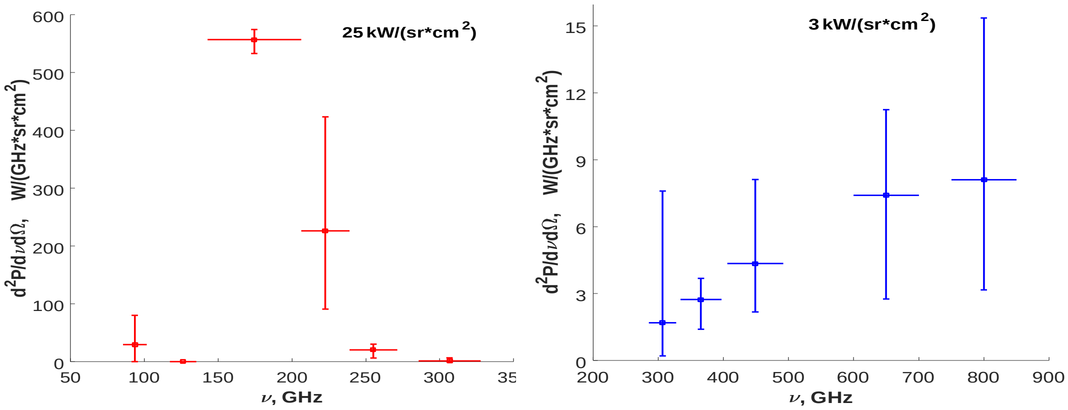


Fig.3. Spectral composition of the plasma emission along the axis in case of strong plasma density gradient in transverse direction.

instability, sub-luminal beam-driven modes can resonate with slow waveguide electromagnetic modes [5]. Then, these waveguide modes escape from the local density wells in the predominantly longitudinal direction via regular longitudinal inhomogeneity of plasma density on the scale of the magnetic field corrugation (10 cm).

As to the high-frequency band 400÷800 GHz, this emission, on our opinion, is a result of the coalescence of two upper hybrid plasma waves into electromagnetic ones [6-8]. Since the sub-mm wave emission at the plasma density higher than 5×10^{14} cm^{-3} is realized along the axis, we suppose that additional feature exists for longitudinal redirection of electromagnetic waves in the GOL-PET device. Note that the tendency to this redirection is qualitatively reproduced in theory [8].

Conclusion. It is found that the radiation spectrum is mainly concentrated in two clearly distinct regions with the high level of spectral power density. For the plasma density $(0.5\div1)\times10^{15}$ см$^{-3}$, the first region is located in the frequency interval f_1=0.15÷0.25 THz, the second one is in the interval f_2=0.4÷0.8THz. It is established that the emission observed in the frequency interval f_1 is interpreted as result of the linear conversion of the upper-hybrid branch of plasma oscillations to the electromagnetic radiation in regions of strong plasma density gradients. We interpret the emission in the interval f_2 as result of merging of these two plasma oscillations into the electromagnetic wave at a high level of plasma turbulence.

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